修 士 論 文 の 和 文 要 旨

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論 文 題 目	Adaptive Band and Power Control for Spectrum Shared Mobile Systems 適応的なスペクトラムバンド分割と電力制御を 用いた周波数共用手法の検討		

要　旨

5G では通信ニーズの多様化に伴い，利用目的に特化した 5G 環境を柔軟に構築可能なプライベート 5G が注目されている．プライベート 5G では，複数の事業者が同一のスペクトラム帯域でスモールセルを展開すること想定されており，周波数の共同利用が求められる．複数セル環境下においては，各セルの相互干渉量に応じて周波数共用の可否が決まるため，干渉電力値を制御し，周波数共用要件を満たすセル数の最大化が重要な課題となる．干渉電力値は，通信エリア周辺の電波環境特性に強く依存することが知られており，高精度な電波環境推定手法として，実観測型スペクトラムデータベースが提案されている．スペクトラムデータベースは，移動端末が観測した電波環境情報を場所ごとに統計化することで，任意の場所の電波環境を高精度に予測することが可能となる．既存のスペクトラムデータベースを活用した周波数共用手法は，異なるプライオリティのシステム及びユーザ間の共用シナリオに向けた手法がほとんどである．また，周波数共用の関連研究では，周波数共用可能なセル数を評価しているが，シャドウイングやマルチパスフェージングと電波伝搬の確率的変動要素は考慮されていない．そこで本論文は，プライベート 5G 向けの周波数共用環境を想定し，スペクトラムデータベースと連携して，電波伝搬の確率的変動要素を考慮した電力制御アルゴリズムを提案する．この手法により，各セルの保護規範を満たしつつ，共用可能なセル数が最大化されることを示す．一方，この手法では複数のセルが近距離で周波数の共用を行う場合，全体のセルのスループットが著しく低下する恐れがある．そこで本論文は，先に提案した電力制御アルゴリズムのスループットの向上に着目し，スペクトラムの分割割り当てを電力制御に組み込んだアルゴリズムを提案する．このアルゴリズムにより，共用環境のセル配置に応じてシステム全体のスループットが最大となるように分割割り当てか電力制御を選択，また実行することが可能となる．従って，本論文では，プライベート 5G 環境での周波数共用において，一つ目の提案手法により，電波伝搬の確率的変動要素を考慮した保護規範を満たしつつ，共用可能なセル数を最大化することで貢献し，さらに二つ目の提案手法により，スループットにおいても最大化することで貢献する．

令和元年度　修士論文

Adaptive Band and Power Control for Spectrum Shared Mobile Systems

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提出日	令和 **2** 年 **1** 月 **27** 日

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和文概要

5G では通信ニーズの多様化に伴い，利用目的に特化した 5G 環境を柔軟に構築可能なプライベート 5G が注目されている．プライベート 5G では，複数の事業者が同一のスペクトラム帯域でスモールセルを展開すること想定されており，周波数の共同利用が求められる．複数セル環境下においては，各セルの相互干渉量に応じて周波数共用の可否が決まるため，干渉電力値を制御し，周波数共用要件を満たすセル数の最大化が重要な課題となる．干渉電力値は，通信エリア周辺の電波環境特性に強く依存することが知られており，高精度な電波環境推定手法として，実観測型スペクトラムデータベースが提案されている．スペクトラムデータベースは，移動端末が観測した電波環境情報を場所ごとに統計化することで，任意の場所の電波環境を高精度に予測することが可能となる．既存のスペクトラムデータベースを活用した周波数共用手法は，異なるプライオリティのシステム及びユーザ間の共用シナリオに向けた手法がほとんどである．また，周波数共用の関連研究では，周波数共用可能なセル数を評価しているが，シャドウイングやマルチパスフェージングと電波伝搬の確率的変動要素は考慮されていない．そこで本論文は，プライベート 5G 向けの周波数共用環境を想定し，スペクトラムデータベースと連携して，電波伝搬の確率的変動要素を考慮した電力制御アルゴリズムを提案する．この手法により，各セルの保護規範を満たしつつ，共用可能なセル数が最大化されることを示す．一方，この手法では複数のセルが近距離で周波数の共用を行う場合，全体のセルのスループットが著しく低下する恐れがある．そこで本論文は，先に提案した電力制御アルゴリズムのスループットの向上に着目し，スペクトラムの分割割り当てを電力制御と併用するアルゴリズムを提案する．このアルゴリズムにより，共用環境のセル配置に応じてシステム全体のスループットが最大となるように分割割り当てか電力制御を選択，また実行することが可能となる．従って，本論文では，プライベート 5G 環境での周波数共用において，一つ目の提案手法により，電波伝搬の確率的変動要素を考慮した保護規範を満たしつつ，共用可能なセル数を最大化することで貢献し，さらに二つ目の提案手法により，スループットにおいても最大化することで貢献する．

Abstract

With the diversification of communication needs in 5G, private 5G, which can flexibly construct a 5G environment specialized for use, has attracted attention. In private 5G, it is assumed that multiple operators deploy small cells in the same spectrum band, and shared use of spectrum is required. In a multi-cell environment, whether or not spectrum sharing is possible depends on the amount of mutual interference between the cells. Therefore, it is important to control the interference power and maximize the number of cells that satisfy the spectrum sharing requirements. It is known that the interference power strongly depends on the radio environment characteristics around the communication area, and measurement-based spectrum database has been proposed as a highly accurate radio environment estimation method. The spectrum database makes it possible to estimate the radio environment at an arbitrary location with high accuracy by statistically analyzing the radio environment information observed by the mobile devices for each location. Most of the spectrum sharing methods using the existing spectrum database aim at sharing scenarios between systems or users of different priorities. In the related work on spectrum sharing, the number of cells that can share spectrum is evaluated, but the fluctuation factors of radio propagation such as shadowing, multipath fading, are not considered. Therefore, we propose a power control algorithm that considers the fluctuation factor of radio propagation in cooperation with the spectrum database, assuming a spectrum sharing environment for private 5G. We show that this proposed method maximizes the number of shareable cells while satisfying the protection criteria of each cell. On the other hand, in this proposed method, when multiple cells share a spectrum at close range, the throughput of the whole cell may decrease significantly. Therefore, we focus on improving throughput of previously proposed power control algorithm and propose an algorithm that incorporates spectrum divide allocation into power control. With this algorithm, it is possible to select and execute divide allocation or power control so that the throughput of the overall system throughput is maximized according to the cell arrangement in the shared environment. Therefore, in this thesis, in the private 5G, the first proposed method contributes by maximizing the number of shareable cells while satisfying the protection criterion considering the fluctuation factors of radio propagation. Furthermore, the second proposed method contributes to maximizing throughput.

Contents

Chapter 1

Introduction

This thesis describes the master's research on effective utilization of the spectrum resources, especially spectrum sharing technologies based on the measurement-based spectrum database. This chapter introduces this field background. After that, we give the research motivations and contributions.

1.1 Background

Since the advent of the first generation mobile communication systems (1G), people's jobs, lifestyles, and various industries have been greatly affected. Mobile communication technologies are the foundation of mobile device communication services that are indispensable to people's lives, such as telephone, searching, watching videos, electronic payments, etc., and the demand is increasing significantly as much as utilities.

According to the report [1], the monthly data traffic is expected to increase by about 6.4 times from 12 exabytes to 77 exabytes between 2017 and 2022 in Figure 1.1. Furthermore, the increase in the number of devices is one of the primary factors to the growth of global mobile traffic and it is expected that the number of mobile devices will become 12.3 billion by 2022. To cope with the growth of data traffic, massive device connection and novel connection services, 5th Generation mobile communication systems (5G) have attracted attention [2]. 5G realizes more enhanced mobile broadband compared with conventional mobile services. Additionally, realizing innovation such as ultra-reliable and low latency communications and massive machine type communication, the usage environment of the wireless communication system be able to provide flexibly according to multifarious demands. In the near future, 5G will not only be an extension of conventional mobile communication systems but also will contribute Internet of Things and realize the internet of vehicles, smart homes, smart cities, industry, medical,

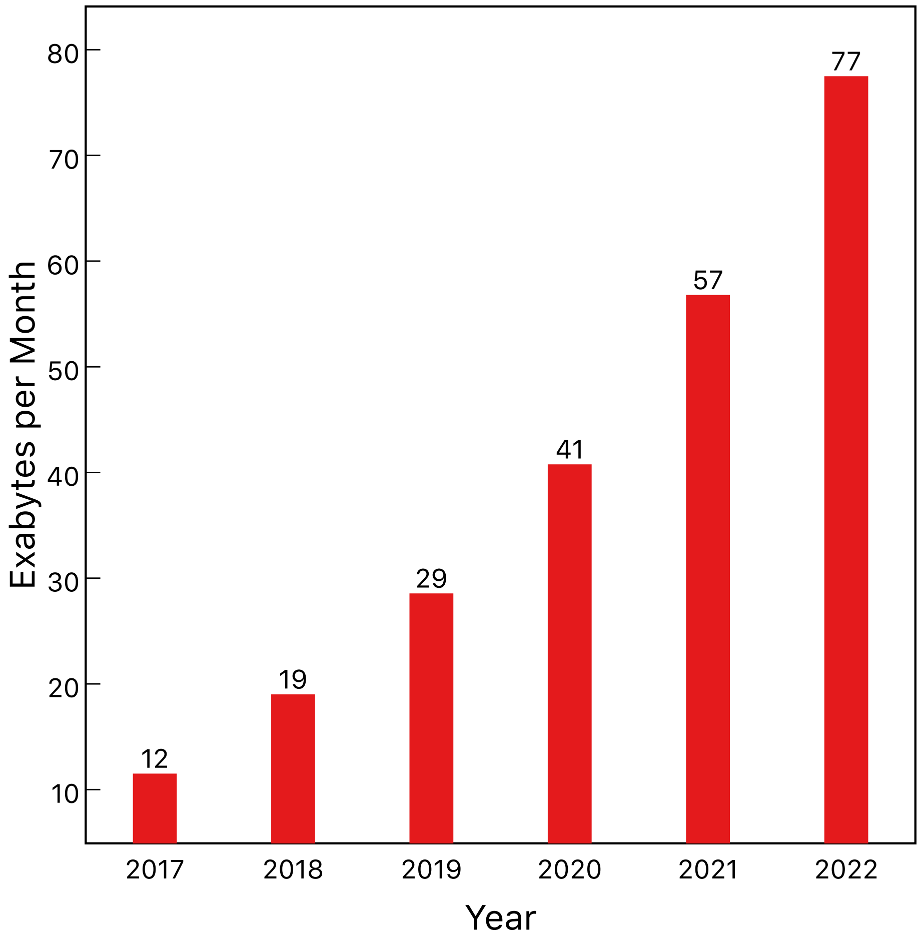

Figure 1.1: Cisco forecast of mobile data traffic per month to 2022 [1].

transportation.

On the other hand, with the diversification of communication needs, private 5G, which can flexibly build a 5G usage environment specialized for the administrator's purpose, such as data traffic, communication area, and network topology, is being discussed by government and company [3–6]. In Japan, in addition to the provision of 5G nationwide services by mobile network operators (MNO), Local 5G, 5G that can be flexibly constructed and used by various organizations according to local demands and individual demands in the industrial field, have been considered [7]. Therefore, In the 5G era, it is expected that a hybrid network that uses both a form in which private operators install base stations themselves and a form in which base stations are installed by MNO will be mainstream.

On the other hand, the serious shortage of spectrum resources has become a problem around the world, and much debate and research activity has been generated. In the first place, the gov-

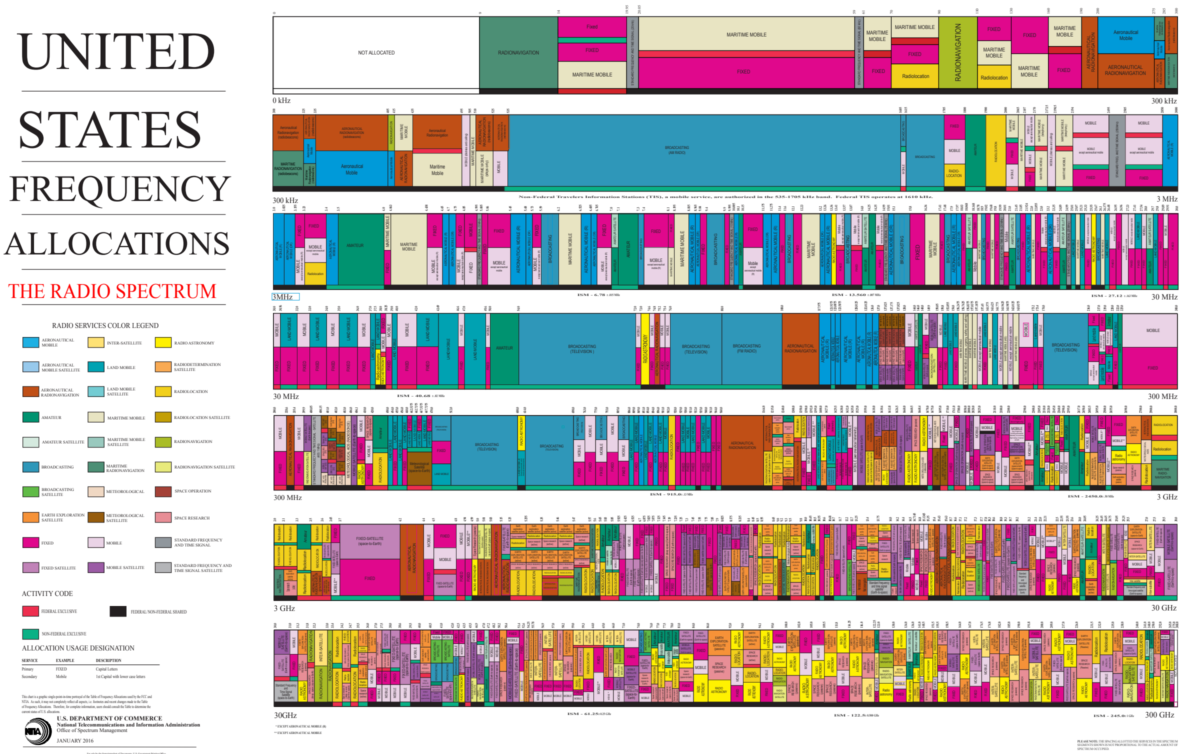

Figure 1.2: The United States of spectrum allocations.

ernments of each country have enacted the radio law, to supervise radio to prevent interference and jamming in the same spectrum band, and have allocated spectrum bands to various services. However, there is a limit to the additional allocation of spectrum, which is a finite resource, so it is highly likely that it cannot cope with the explosive increase of mobile data traffic.

Figure 1.2 summarizes the spectrum allocations in the United States [8]. This shows that even as of January 2016, almost all of the spectrum band has already been allocated to some system. Furthermore, the situation where two or more systems share the same spectrum band is dominant. Therefore, in such a situation, it is not practical to allocate a new wireless system. Furthermore, when considered in a system unit as a cellular system, there is a possibility that congestion occurs in a specific band, and the desired communication quality may not be obtained. Therefore, the shortage of spectrum resources is a fundamental problem in current mobile communication systems, and governments and MNOs in each country need to take measures such as introducing technologies with high spectrum efficiency.

As mentioned, most of the spectrum is allocated to wireless systems and services. However, it has been reported that the actual time and space spectrum band utilization is low and that spectrum may not be used efficiently [9]. The reason is that, as shown in Fig. 1.3, the congestion

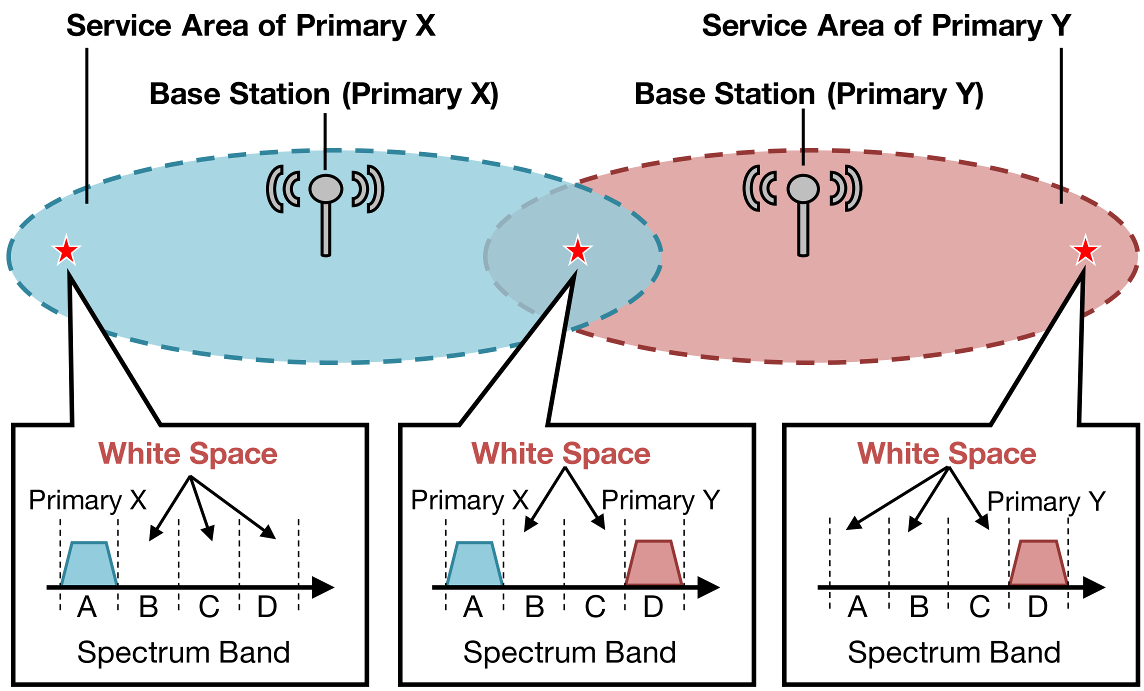

Figure 1.3: Example of spatial white space.

situation in which various radio fly differs depending on the time and area. The spectrum that is allocated to some systems or services but not used under specific times or areas is called white space, and effective use of white space is required around the world [10, 11].

In recent years, various research institutions are attracted attention to spectrum sharing technologies, in which white space is shared by multiple systems and users, as a solution to the shortage of spectrum resources problem [12–16]. Spectrum sharing requires secondary users (SU) to share spectrum in a spectrum band to which the system has already been allocated, without interfering with the primary user (PU). Moreover, in private 5G such as local 5G in Japan, it is required to study a method of sharing spectrum between private 5G with the same priority. In spectrum sharing, PU communication has absolute priority, so when SU shares spectrum, it is necessary to guarantee the communication quality of PU. Therefore, the amount of interference power of SU to PU should be managed to an appropriate value. Additionally, even in private 5G with the same priority, it is necessary to control the amount of mutual interference and guarantee mutual communication quality. Since the amount of interference is determined by the communication parameters of the SU and the radio propagation characteristics, it is very important to estimate this characteristic. Estimation accuracy has been discussed by various research institutions because it has a significant effect on the performance of spectrum sharing.

As one of the radio environment estimation technologies, there is an empirical radio propagation model. This model is the most basic method, and the equation is modeled experimentally. However, there is a problem that the radio environment is roughly classified into urban, suburban, rural, etc., and because it is measured in the experimental environment at that time, there is a high possibility that it does not match the current environment. Furthermore, this model considers the distance between the transmitter and the receiver and the antenna height, and so on, but does not support fluctuation factors such as shadowing and fading [17]. Therefore, it is necessary to provide a protection margin for determining the transmission power of the SU taking into account the estimation error, and the white space may not be fully utilized.

As one of the highly accurate radio environment estimation methods, measurement-based spectrum database has attracted attention [18–20]. In the database, the observation results of the radio environment information observed by a huge number of mobile terminals are aggregated, and a radio environment map (REM) is created based on the data observed, enabling highly accurate radio environment estimation. By utilizing REM, terminals can accurately predict path loss and shadowing, and be used to design communication parameters. Therefore, a dramatic improvement in spectrum efficiency can be expected by the database.

Most of the examples of database utilization for spectrum sharing are for spectrum sharing scenarios with different priorities, such as PU and SU. The database has not yet been introduced for spectrum sharing in an equal priority shared environment where multiple private 5G operators deploy small cells. In an environment where such priorities are equal and there are multiple private 5G operators, it is important to accurately construct the database of the radio environment in each cell. Besides, by controlling the interference power and spectrum bandwidth based on the database, it is necessary to achieve spectrum sharing requirements such as suppressing the interference probability less than the permissible value in all cells and maximizing the number of shareable small cells.

In the related work on spectrum sharing, the number of shareable small cells is evaluated in a spectrum sharing environment between multiple SUs. However, the radio propagation model is used as a radio environment estimation method, and the effects of shadowing and multipath fading are not clear.

The shadowing components have a spatial correlation and can be estimated with high accuracy by using the database . On the other hand, multipath fading is difficult to estimate using the database that stores REM. On the other hand, it is well known that the performance of spectrum sharing strongly depends on the multipath fading characteristics. In particular, deep fades can affect Signal-to-Interference plus Noise power Ratio (SINR) and degrade the performance of spectrum sharing. To achieve strict and accurate spectrum sharing, it is necessary to accurately estimate the multipath fading characteristics in addition to path loss and shadowing. In addition, the interference power must be designed based on the estimation results, and small cells must be placed as tightly as possible while keeping the interference probability within a certain level.

1.2 Purpose of the Research

In this thesis, we propose a spectrum sharing method based on a power control algorithm that guarantees the desired SINR in each small cell considering the multipath fading factor and maximizes the number of small cells that can share the same spectrum. In the proposed method, the database estimates the SINR probability distribution for each cell and designs the interference power based on the estimated probability distribution. Then, power control that satisfies the permissible outage probability is performed to maximize the number of spectrum sharing small cells in a particular area.

After the power control algorithm is established, we propose a spectrum sharing method based on an algorithm that combines adaptive spectrum band division with power control to improve the throughput of each cell. This method is effective when multiple cells share the same spectrum at a short distance. This is because the mutual interference power increases, so it is necessary to reduce the transmission power of the cell excessively, and there is a risk that the throughput is greatly reduced.

To evaluate the two proposed methods, computer simulations are performed to derive spectral sharing performance. In the first proposed method, it is possible to confirm that a high-density small cell can be realized by using the proposed method on the same spectrum while maintaining the outage probability compared to the method without power control. In the second proposed method, the usefulness is confirmed by deriving the overall system throughput when adaptive division is combined with power control and when it is not.

This thesis is organized as follows. Chapter 2 describes the spectrum database and its related basic knowledge. In chapters 3 and 4, the proposed method of spectrum sharing using transmission power control algorithm and adaptive spectrum band divide algorithm is explained, and its usefulness is shown by numerical simulation. Finally, we summarize this thesis in chapter 5.

Chapter 2

Measurement-based Spectrum Database

This chapter expresses concept of the measurement-based spectrum database. In particular, the architecture of spectrum database and how to collect radio environment information and the benefits are particularized.

2.1 Architecture of Spectrum Database

In particular, it focuses on the construction of the spectrum database and the collection method and advantages of radio environment information.

Figure 2.1 shows the concept of the spectrum database. The mobile devices measure the radio environment around the cell and, along with the latitude and longitude position information, the network type, measurement time, received signal power, strength indication, center frequency, physical cell ID, CQI and so on. Then, the mobile devices record in the database via cellular line or Wi-Fi. After sufficient data has been collected, the data set is used for statistical processing in units of mesh determined by latitude and longitude. A mesh is managed by a

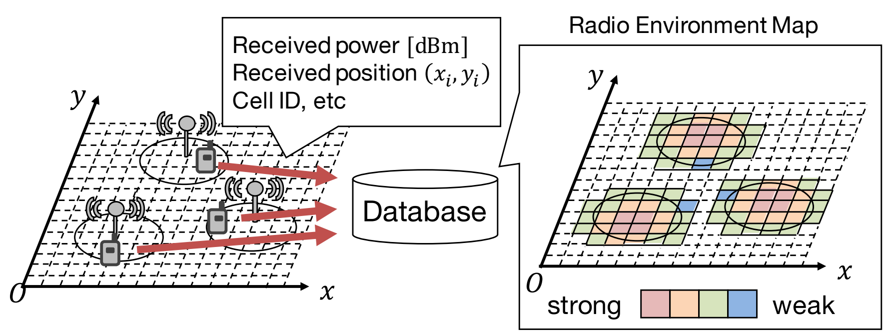

Figure 2.1: Concept ot the measurement-based spectrum database.

unique character string called a mesh code. A well-known example of statistical processing is the averaging of data samples for each mesh used in REM. Such a measurement-based database can estimate the radio environment with higher accuracy. However, to build the database based on actual observations, if the information on regions around the world is aggregated into the database, the amount of data will be enormous and it will be difficult to operate the database. Therefore, a hierarchical database structure is being studied [19]. Figure 2.2 shows the structure of the hierarchical spectrum database.

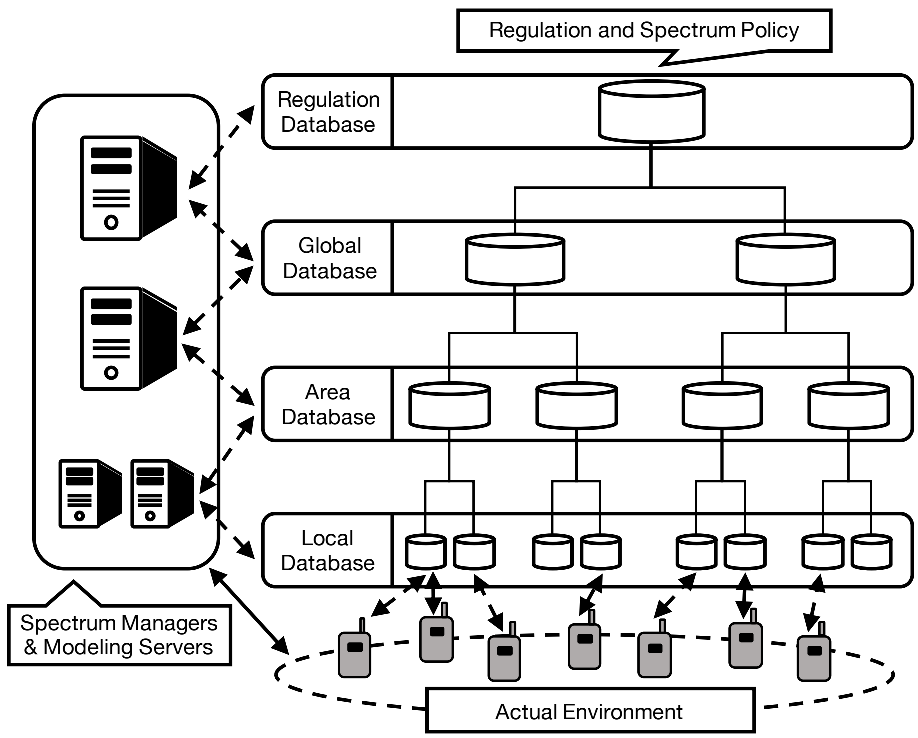

Figure 2.2: Hierarchical spectrum database.

The hierarchical database stores the information observed by the mobile devices in the database that manages the lowest local area. The local database can record information of actual observation values with fine granularity and can use the collected observation information to realize efficient spectrum utilization. However, if the database of actual observations is constructed in a wide area such as a country, the operation becomes difficult due to the huge amount of data. Therefore, the database has a hierarchical structure, and the statistical processing data collected in the local database is stored in the area database, which is the next higher layer, and the propagation of the surrounding area can be estimated. The upper layer can manage the global area. For example, multiple regional spectrum conditions must be considered in the management of national and regional boundaries. Such large-span spectrum utilization can be supported by the global database. The highest layer defines radio regulation and spectrum policy that is being considered by radio management organizations such as FCC and the Ministry of Internal Affairs and Communications. The regulator can manage this higher-level database and change spectrum allocation, change policies, and share spectrum. The database of each layer is connected to the spectrum manager and the modeling server, and manages the spectrum utilization rate and performs modeling of the radio environment.

2.2 Collection of Radio Environment Information with Crowdsensing

To construct a highly reliable database, a vast amount of radio environment information with a wide range and high density is required. Hierarchical spectrum databases can achieve this by utilizing crowdsensing [21,22]. Figure 2.3 shows an overview of crowdsensing. Crowdsensing, also called mobile crowdsensing, was coined by Raghu Ganti, Fan Ye, and Hui Lei. Mobile crowdsensing is a technology that obtains large amounts of data from a crowd using mobile devices (smartphones, tablets, cars, etc.) equipped with sensing, computing. In addition, this technology analyzes, maps, and estimates the acquired data and uses it for various applications. In a modern society where the number of mobile devices is expected to be 12.3 billion by 2020 [1], the use of mobile devices that are already widespread can reduce the introduction cost. It is no exaggeration to say that crowdsensing is one of the most effective technologies for collecting radio environment information in the spectrum database. The registered information is updated regularly to support changes in the radio environment.

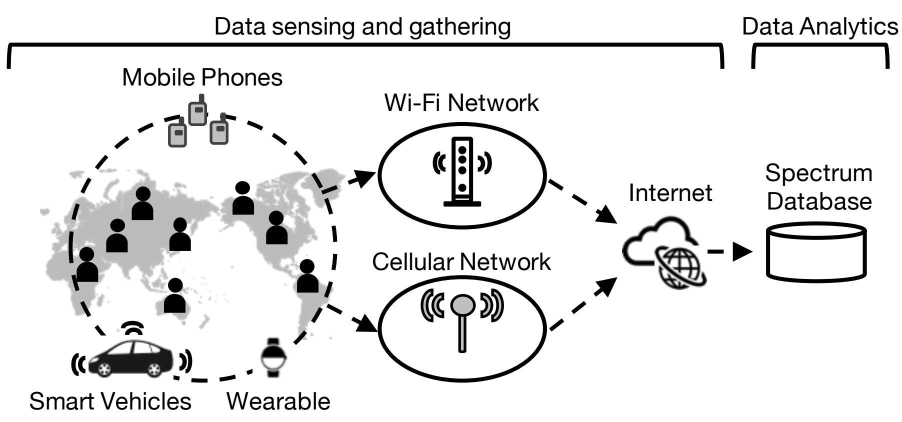

Figure 2.3: Overview of crowdsensing.

2.3 Radio Environment Map

An example of using the spectrum database is estimating a radio environment map [23, 24]. The radio environment map is a map that visualizes the spatial spread of the average received power. The average received power is calculated for each mesh determined based on the location information of the mobile device and is managed in mesh units. Each mesh is accompanied by a mesh code, which can be managed uniquely in the database. In Japan, regional mesh codes used for regional meshes, and world meshes that extend it and uniquely assign meshes to all places in the world are being considered. Table 2.1 shows definition of the mesh codes by JISX0410 and there is a primary to standard mesh, and 1/2 mesh and 1/4 mesh and 1/8 mesh below it. The length of one side is about 80 [km] in the upper mesh and about 125 [m] in the lower mesh. The mesh size can be changed according to the utilization of the radio environment map. When the number of actual observations in the radio environment map creation area is enormous, the reliability of the radio environment map is maintained even if the mesh size is reduced. As a result, it is possible to predict the fluctuation of the received signal power due to the distance attenuation and shadowing at an arbitrary position from the transmitter with high accuracy. An example of the radio environment map is shown in the figure. This is a map created by the author by performing radio observation experiments in Sapporo City, Hokkaido.

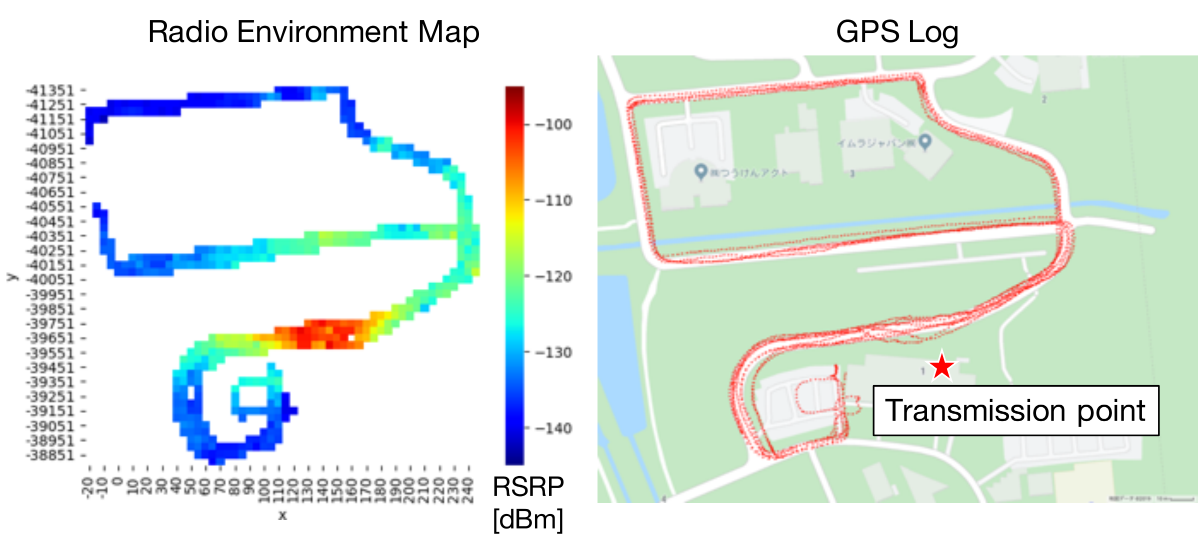

Figure 2.4: Example of the radio environment map.

Table 2.1: Definition of mesh code classification.

Mesh type	Descriptions	Interval		Approximate size of sides
		Latitude	Longitude	
Primary	Areas formed by dividing the nationwide area by latitudes and even longitudes at even-numbered latitudes and at three equal intervals.	40 minutes	1 degree	80 [km]
Secondary	An area where the primary area is divided into eight equal parts in the parallel and meridian directions.	5 minutes	7.5 minutes	10 [km]
Standard mesh	An area where the secondary area is divided into 10 equal parts in the parallel and meridian directions.	30 seconds	45 seconds	1 [km]
1/2 mesh	An area where the standard mesh is bisected in the latitude and longitude directions.	15 seconds	22.5 seconds	500 [m]
1/4 mesh	An area that can be obtained by bisecting the 1/2 mesh in the latitude and longitude directions.	7.5 seconds	11.25 seconds	250 [m]
1/8 mesh	An area that can be obtained by dividing the 1/4 mesh into two equal parts in the latitude and longitude directions.	3.75 seconds	5.625 seconds	125 [m]

2.4 Estimation of Probability Distribution

In wireless communication, signal power undergoes a fluctuation factor called fading due to the movement of terminals and changes in the surrounding environment. In the radio environment map, the fading component is removed because the averaging process is performed on the actual observation value. Hence, even if the average received power is obtained from the radio environment map and the interference power is designed for spectrum sharing, there is a possibility that large fluctuations in the received power due to instantaneous fading may cause significant interference to the communication system. Therefore, by estimating the probability distribution of the received signal power for each mesh, it is possible to recognize the radio environment including fading. As a result, the system can be protected in consideration of the probability of occurrence of interference, and the performance of spectrum sharing can be greatly improved. In this thesis, we propose a spectrum sharing method utilizing the probability distribution estimated by this spectrum database.

Chapter 3

Spectrum Sharing based on Transmission Power Control Algorithm

Chapter 2 gives an overview of the actual observation type spectrum database and its benefits. In this chapter, we propose a spectrum sharing method using a spectrum database in a private 5G environment. Specifically, we describe a method of estimating the interference probability from a database and designing the transmission power of each cell so that small cells with the same priority do not cause harmful interference to each other.

3.1 System model

Figure 3.1 shows the system model. It is assumed that multiple private 5G operators place small cells in a spectrum sharing assumed environment. It is assumed that all cells communicate in the same spectrum band and that outdoor public spaces are shared.

Mobile devices upload the radio environment information of each small cell to the spectrum database and the information is statistically processed by the database server. Each small cell design transmission power based on statistical information to realize spectrum sharing with high spectral efficiency. Each cell is formed from the base station, and the cell radius is set to a distance such that signal power-to-noise power ratio (SNR) is a desired value. As shown in Fig. 3.2, an arbitrary cell is defined as a target cell and it is subject to communication protection. Furthermore, the interference cell is defined if the interference power to the target cell is larger than the noise power. In this thesis, the transmission power is controlled in each cell so as to satisfy a protection criterion described later in the target cell. Moreover, the target cell is sequentially changed to satisfy the protection criterion in all cells.

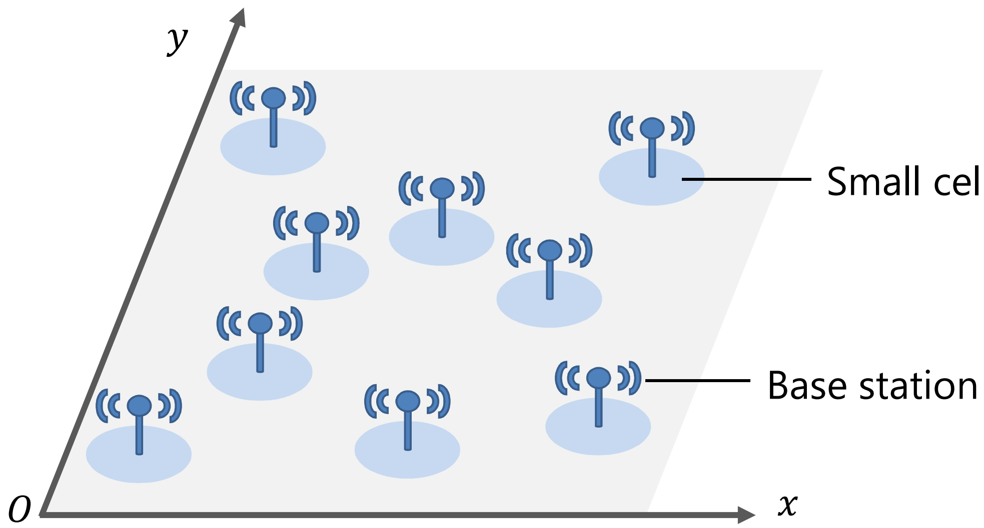

Figure 3.1: Spectrum sharing model.

3.2 Spectrum Sharing Requirements

In this thesis, we use SINR as the protection criterion for the target cell and express as follows:

$$\mathrm{SINR_{ins}} = \frac{P}{\sum_{i=1}^{n} I_i + N}, \tag{3.1}$$

where P is the received signal power observed by the mobile device, I_i is the received signal power from the interference cell observed by the mobile device, n is the number of the interference cells, N is Average Noise Power. In this thesis, the outage event is defined that the instantaneous SINR falls below the desired SINR. The protection criterion is expressed as follows:

$$\Pr\left[\mathrm{SINR_{ins}} \geq \mathrm{SINR_d}\right] \geq 1 - p_{\mathrm{out}}, \tag{3.2}$$

where $\mathrm{SINR_{ins}}$ is instantaneous SINR, $\mathrm{SINR_d}$ is desired SINR, p_{out} is permissible outage probability. Each cell controls the transmission power so that the outage probability satisfies the permissible value utilizing the database described later.

3.3 Transmission Power Control Algorithm

This section describes the structure of the spectrum database applied to the transmission power control algorithm and the estimation of the probability distribution. Next, we describe a power control algorithm that maximizes the number of cells that can share a spectrum while guaranteeing an acceptable outage probability.

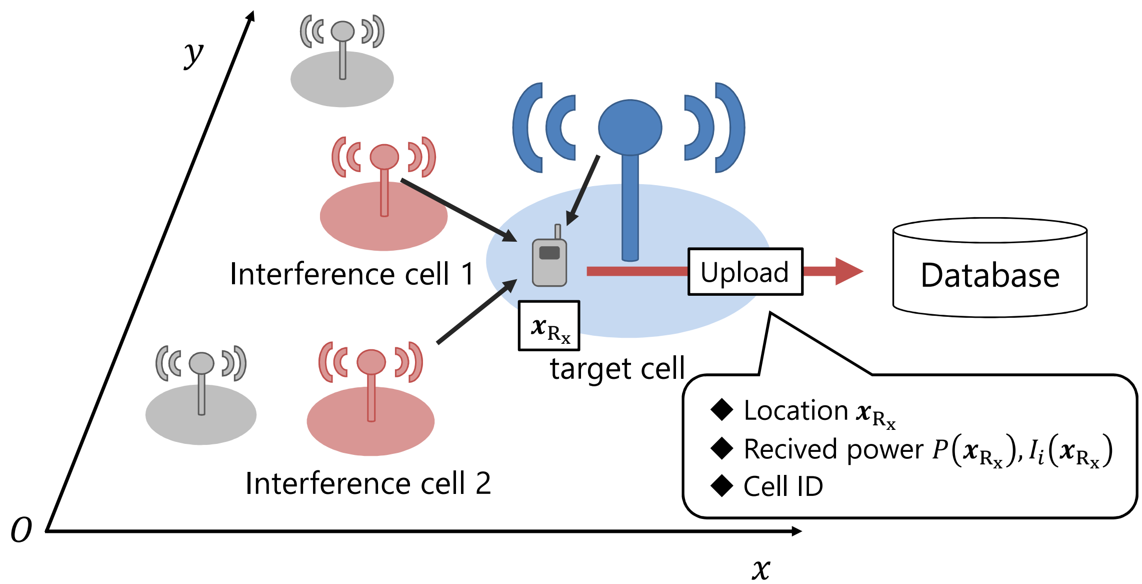

Figure 3.2: Concept of the spectrum database for spectrum sharing in this research.

3.3.1 Measurement-based Spectrum Database

In this chapter, since SINR is used as the protection criterion, the database that stores the received signal power of the own cell and the received signal power of the interference cell is constructed by applying the spectrum database in chapter 2.

Figure 3.2 shows the concept of the spectrum database for spectrum sharing in this research. The mobile terminal observes the radio environment around the cell and records information such as received time, received position, received signal power, center frequency, and cell ID. In particular, as mentioned in Sect. 3.2, we utilize SINR as the protection criterion. Therefore, it stores not only the received signal power in its own cell but also the interference signal power from the interfering cell in the database. The database needs to identify the cell ID of the signal to calculate the SINR. Thus, it is assumed that the transmission packet includes the cell ID, and when the packet demodulation succeeds, the terminal can be accurately identified the cell ID. Then, the stored information is reported to the database server via Wi-Fi or cellular network. Then, the database statistically processes the measurement datasets in each two-dimensional square meshes. Here, the mesh code is assigned to each mesh, and it is calculated along the latitude and longitude of the measurement datasets. By utilizing the statistical information, the terminal can estimate path loss and shadowing at an arbitrary location with high accuracy and utilize for designing the communication parameters.

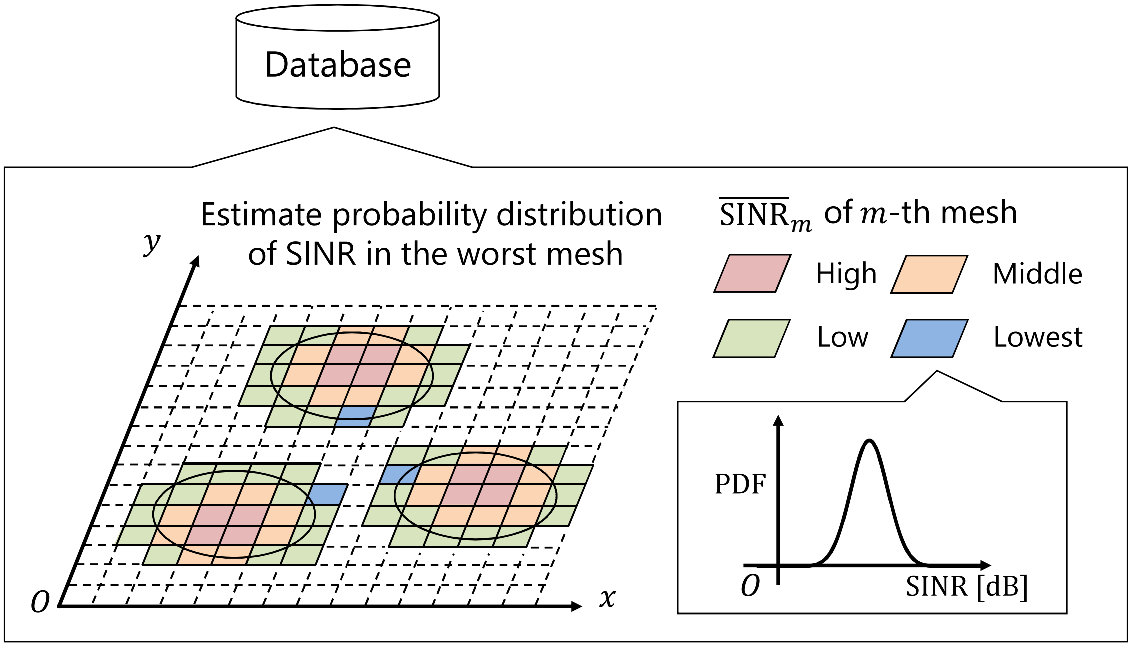

Figure 3.3: Estimate probability distribution of SINR in worst mesh.

3.3.2 Probability Distribution Estimation

In this thesis, it is necessary to strictly satisfy the protection criterion defined by (3.2) in each cell. However, SINR instantaneously fluctuates due to shadowing and multipath fading, hence the protection criterion may not be strictly satisfied. Therefore, as shown in Fig. 3.3, we propose the database that estimates the probability distribution of SINR at the edge of the target cell. In this thesis, we define a mesh where the minimum average SINR exists of target cell as *the worst mesh*. Moreover, we judge whether spectrum sharing is possible or not based on the probability distribution of SINR in the worst mesh. The details are explained in Sect. 3.3.3. First, the database calculates the average SINR for each mesh and decides the worst mesh where the minimum SINR exists. On the database, the average SINR is calculated for each mesh based on the measurement datasets using the following equation:

$$\overline{\mathrm{SINR}}_m = \frac{1}{J}\sum_{j=1}^{J}\left(\frac{P}{\sum_{i=1}^{n} I_i + N}\right), \tag{3.3}$$

where m is the mesh number, and J is the number of measurement datasets in the mesh.

Next, the database estimates the probability distribution of SINR in the worst mesh. In this thesis, it is assumed that path loss and shadowing in the mesh are negligible, and only the multipath fading affects the distribution of SINR. As a method of distribution estimation,

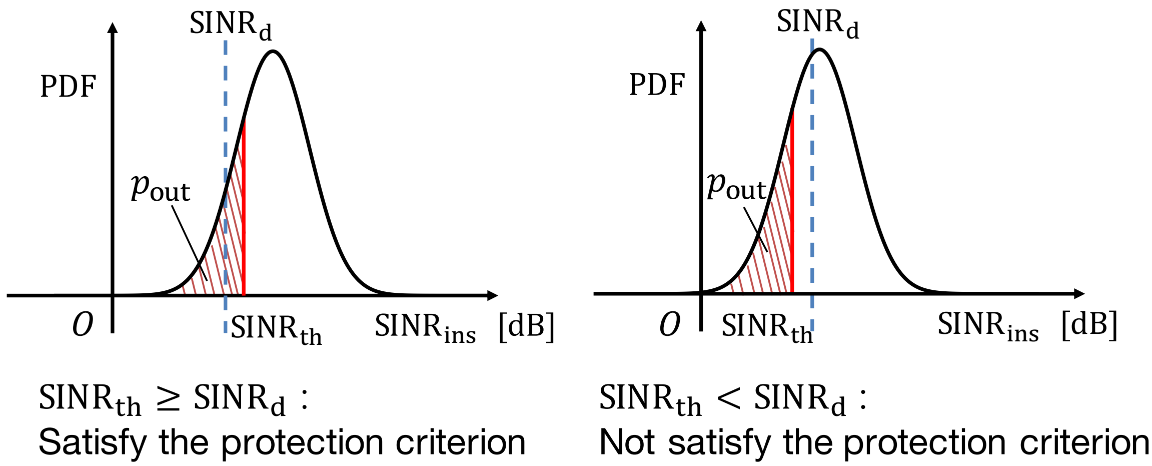

Figure 3.4: Determining whether the protection criterion is satisfied.

a logarithmic value of instantaneous SINR in (3.1) is calculated, and a lower percentage point $\mathrm{SINR_{th}}$ [dB] that is defined the cumulative probability of the $\mathrm{SINR_{ins}}$ falls below than the permissible outage probability p_out is empirically estimated. The accuracy of distribution estimation depends on the number of measurement datasets in the worst mesh. when the number of measurement datasets is sufficiently large, the distribution can be estimated accurately. The above operation is performed by changing the target cell, and the probability distribution of the SINR and the lower percentage point in each worst mesh are accumulated in the database.

3.3.3 Power Control Algorithm

Based on the estimated probability distribution, the transmission power is controlled so that the outage probability less than p_out at the desired SINR in all the cells. Here, as shown in Fig. 3.4, if the lower percentage point $\mathrm{SINR_{th}}$ [dB] is smaller than the desired value $\mathrm{SINR_d}$ [dB], the protection criterion defined in (3.2) cannot be satisfied because the outage probability at $\mathrm{SINR_d}$ is larger than the permissible value p_out. Therefore, to maximize the number of cells that can share the same spectrum, it is necessary to control the transmission power so that $\mathrm{SINR_{th}} \geq \mathrm{SINR_d}$ in all the cells. The power control algorithm is shown below.

Step1

In the worst mesh of each cell, the lower percentage point $\mathrm{SINR_{th}}$ [dB] and the desired value $\mathrm{SINR_d}$ [dB] are compared to determine if the protection criterion is satisfied. When spectrum sharing is possible for all cells, it ends.

Step2

In each cell, the database calculates the total interference power to neighboring cells and lowers the transmission power of the cell with the largest total interference power by P_{Delta} [dBm]. Then, the worst mesh is recalculated in the cell where the power control is performed.

Step3

If the $\mathrm{SINR_{th}}$ is larger than the $\mathrm{SINR_d}$ in all cells, it ends. If the protection criterion does not satisfy, in order to maintain fairness, **Step2-3** is performed with cells other than the cells that have already been subjected to power control in **Step2**. If the protection criterion does not satisfy, even if the power control is performed on all cells, **Step2-3** is performed again on all the cells within satisfying the lower limit of the communication channel capacity $C_{\min}$ [bit/s] at the cell edge. Here, the lower limit value $C_{\min}$ at the cell edge is expressed by the following equation:

$$C_{\min} = W \log_2 \left(1 + \frac{S}{N}\right), \tag{3.4}$$

where W [Hz] is spectrum bandwidth, S is the antilogarithm of the received signal power at the cell edge.

Step4

If the communication capacity of the cell is smaller than the $C_{\min}$ and the protection criterion does not satisfy, the cell with the largest total interference power is excluded from the shared target.

Step5

Using initial cell radius and transmission power, the database executes again from **Step1** and iterates the algorithm until all cells can be shared. This power control algorithm considers the largest interference power that becomes a bottleneck of spectrum sharing. As a result, it is possible to increase the number of cells that can share the same spectrum while suppressing the decrease in the communication channel capacity of each cell. It is assumed that the cells excluded from the spectrum sharing target in **Step4** are assigned to different spectrum bands.

3.4 Performance Evaluation

We simulated the number of cells that can share the same spectrum using power control algorithm via computer simulation.

3.4.1 Simulation Parameters

The simulation specifications are shown in Tab. 3.1. In this simulation, cells are arranged from a uniform distribution in an area of 1,000 * 1,000 $[\mathrm{m}^2]$. The initial radius of the cell is 150 [m] , and initial transmission power is set so that the desired SNR becomes 20 [dB] using only path loss. The lower percentage point $\mathrm{SINR}_{\mathrm{th}}$ is calculated by sorting in ascending order of the instantaneous SINR in each mesh and finding the value that cumulative probability falls below the permissible outage probability p_{out}. Furthermore, the fading assumes Rayleigh distribution and the fading component F [dB] is calculated by converting the random value that follows an exponential distribution with a mean of 1 to the logarithm value. In this simulation, the interference cell is defined if the interference power to the target cell is larger than the noise power by considering only path loss.

3.4.2 Radio Propagation Model

In this simulation, the received signal power $P(\boldsymbol{x}_{\mathrm{R_x}})$ [dBm] at the receiver position $\boldsymbol{x}_{\mathrm{R_x}}$ is modeled as follows:

$$P(\boldsymbol{x}_{\mathrm{R_x}}) = P_{\mathrm{T_x}} - L(d) + F, \tag{3.5}$$

where P_{Tx} [dBm] is the transmission power of the target cell, and $L(d)$ [dB] is path loss , d [m] is the distance between the base station position of the target cell $\boldsymbol{x}_{\mathrm{T_x}}$ and $\boldsymbol{x}_{\mathrm{R_x}}$. F [dB] is the multipath fading. Furthermore, $L(d)$ [dB] is modeled as following equation:

$$L(d) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10n\log_{10}\left(\frac{d}{d_0}\right), \tag{3.6}$$

where d_0 [m] is the reference distance, λ [m] is the wavelength, n is path loss index. Moreover, the interference power $I_i(\boldsymbol{x}_{\mathrm{R_x}})$ [dBm] in i-th interference cell at the receiver position $\boldsymbol{x}_{\mathrm{R_x}}$ is modeled as follows:

$$I_i(\boldsymbol{x}_{\mathrm{R_x}}) = P_{I_i} - L(d) + F, \tag{3.7}$$

Table 3.1: Simulation parameters.

Simulation area [m^2]	1,000*1,000
Mesh size [m^2]	10*10
Initial transmission power [dBm]	30
Average noise power N [dBm]	-95.0
Desired SINR [dB]	5.0
Path loss index	3.5
Reference distance [m]	10
Number of samples for distribution estimation	10,000
Permissible outage probability	0.20

where P_{I_i} [dBm] is the transmission power of the i-th interference cell, and $L(d)$ [dB] is path loss defined in (3.6). F [dB] is the multipath fading.

The SINR is derived by substituting the values calculated by these equations into (3.1).

3.4.3 Characteristic of the number of Shareable Cells

First, the number of cells that can share the same spectrum is shown in Fig. 3.5. In the case of no power control, the number of shareable cells is calculated 0 if there is even one cell whose outage probability exceeds the permissible value. Furthermore, it is assumed that the position of the already arranged cells is not changed when a new cell is added. In the number of cells is 2 to 4, the number of cells that can be shared increases, in both with and without power control. In the number of cells is small, because the distance between the cells may be large, the total interference power to the target cell is small. As a result, the lower percentage point $\mathrm{SINR}_{\mathrm{th}}$ in each worst mesh becomes larger than the desired value $\mathrm{SINR}_{\mathrm{d}}$, and the number of cells that can share the same spectrum is increased. Furthermore, in the number of cells is 5 to 10, the number of cells that can share the same spectrum is different significantly with and without power control. In the number of cells is large, the total interference power to the target cell becomes large. Thus, the outage probability exceeds the permissible value and the number of cells that can share the same spectrum is 0 without power control. On the other hand, in the proposed method, the number of cells that can share the same spectrum is 5. This is because power control is preferentially performed from a cell having the largest interference power and the outage probability decreases in the target cell. Note that, in the number of cells is 5 to 10, the number of cells that can share the same spectrum hardly increases. This is probably because the total interference power to the target cell becomes large and the outage probability exceeds

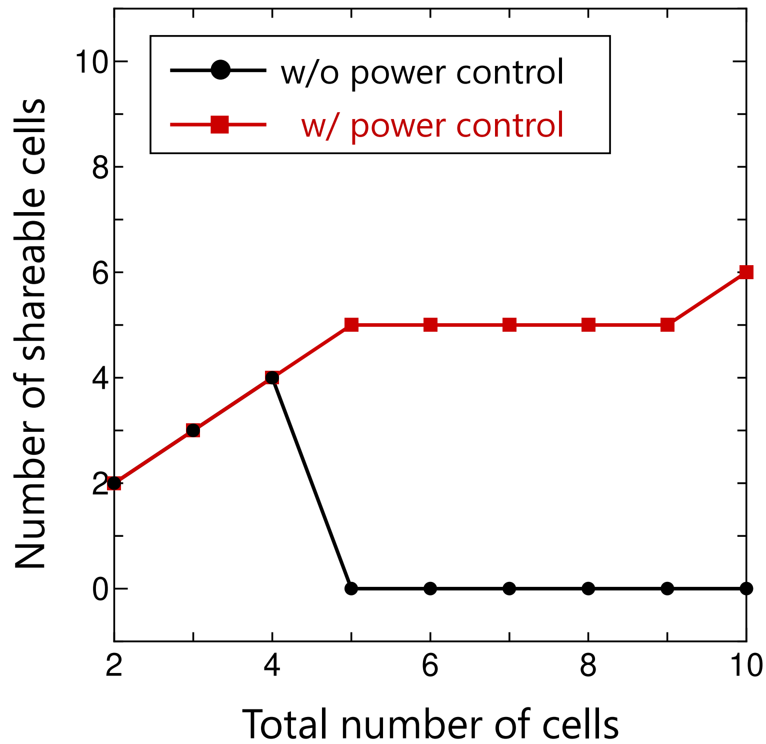

Figure 3.5: Characteristic of the number of shareable cells.

the permissible value in many cells.

3.4.4 Characteristic of Outage Probability

Finally, the outage probability after power control is shown in Fig. 3.6. Note that the vertical axis represents the maximum outage probability among the shareable cells. From Fig. 3.6, we can confirm that the permissible outage probability is satisfied for all 2 to 10 total cells. In the number of cells is 2 to 4, the distance between the cells becomes large and the total interference power to the target cell is small. Hence the maximum outage probability is much lower than the permissible value. On the other hand, the number of cells is 5 or more, it is found that the permissible outage probability can be asymptotically achieved. It is considered that the distance between the cells becomes small and the total interference power to the target cell increases. As a result, it is inferred that the outage probability at each worst mesh became asymptotic to the permissible value.

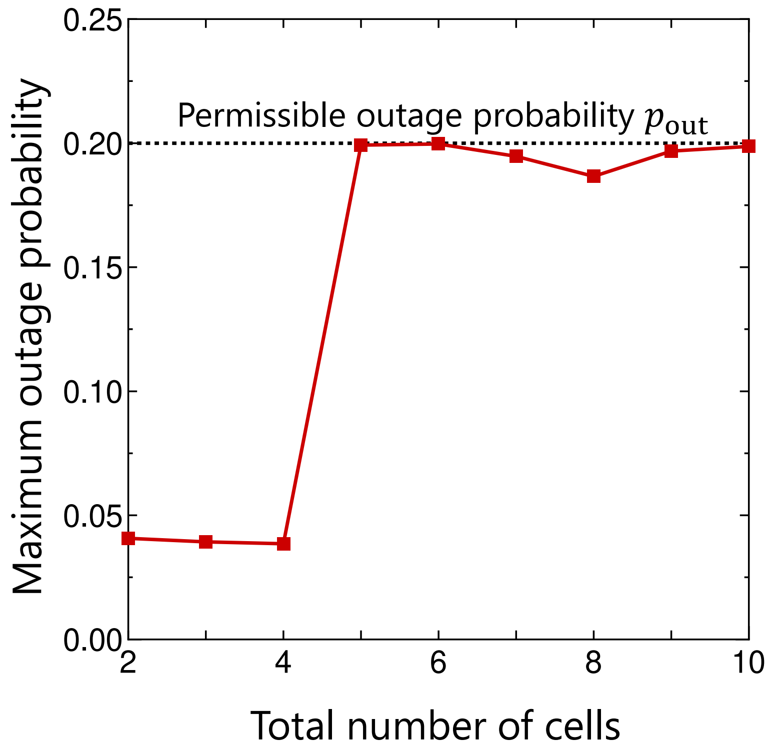

Figure 3.6: Characteristic of outage probability.

3.4.5 Characteristics of Accuracy of Outage Probability

Next, the accuracy of the outage probability when the permissible outage probability is changed is evaluated. Figure 3.7 shows the outage probabilities when the permissible outage probabilities are set to 0.15, 0.2, 0.25, and 0.3. The figure shows that the total number of cells satisfies the permissible outage probability from 2 to 10. Moreover, even if the permissible outage probability is changed, the graph is asymptotic to the value. Figure 3.8 shows the number of shareable cells at this time. According to this results, basically the same as in Fig. 3.5. Hence, it is found that even if the permissible outage probability is slightly changed, the interference amount due to the large number of cells cannot be tolerated. Also, it can be seen that when the permissible outage probability is only 0.15 and the number of cells is 10, the number of shareable cells has decreased by one. However, in the case of other numbers of cells and the permissible outage probability, there is no difference from the case where the permissible outage probability is 0.2. Therefore, when the permissible outage probability is low, there is no correlation between the permissible outage probability and the number of shareable cells.

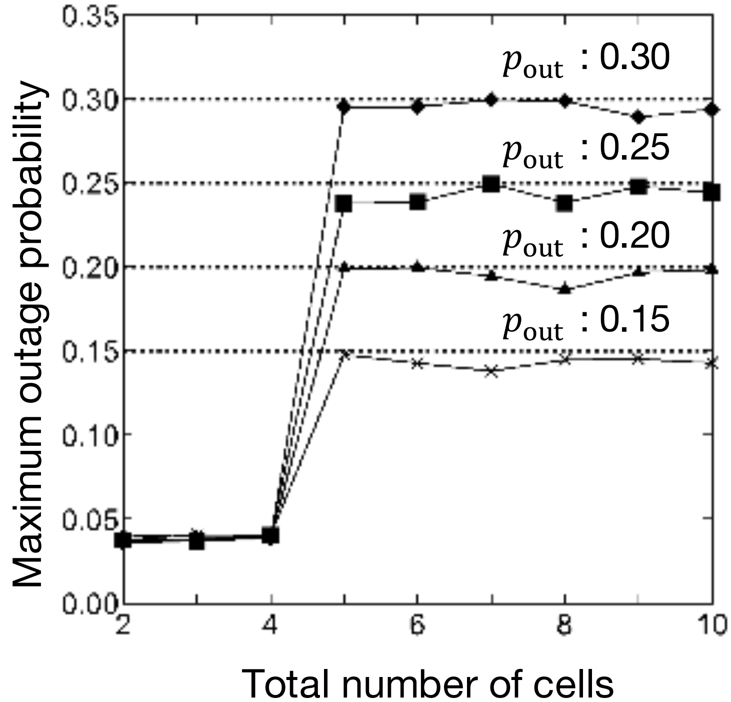

Figure 3.7: Characteristic of permissible outage probability.

3.5 Chapter Summary

In this chapter, we propose the power control method that guarantees the desired SINR in each small cells considering multipath fading factor and maximizes the number of small cells that can share the spectrum. In the proposed method, the probability distribution of SINR in the worst mesh of each cell was estimated. After that, the transmission power control of the cell with the largest total interference power was performed so as to satisfy the permissible outage probability of the protection criterion, and the cell which can share spectrum was maximized. In the results, we can confirm that it is possible to realize a high density cell arrangement while accurately satisfying the permissible outage probability of the shareable cell.

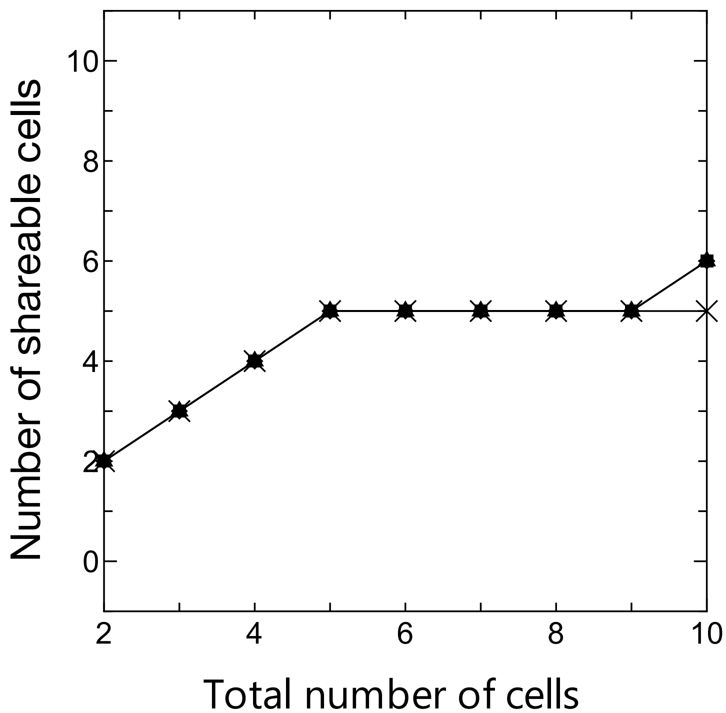

Figure 3.8: Characteristic of the number of shareable cells at each permissible outage probability.

Chapter 4

Spectrum Sharing Combining Power Control and Adaptive Band Control

In chapter 3, spectrum sharing based on a power control algorithm that maximizes the number of small cells while probabilistically guaranteeing communication quality was proposed. However, when multiple private 5G operators deploy small cells at close range, cell throughput can be significantly reduced. The reason for this is that the mutual interference power values are so high that the transmit power of these cells needs to be reduced too much. This chapter proposes a concept of effective spectrum divide allocation for this problem and proposes a spectrum sharing method that maximizes the overall system throughput by combining spectrum divide allocation with a power control algorithm.

4.1 System Model

The system model is the same as the model in chapter 3. However, as the spectrum sharing requirement, the lower limit of the cell edge throughput determined by the private 5G operator in each cell is defined, and this is added to the sharing requirement. This is to guarantee the throughput even in the worst case by setting the lower limit at the cell edge where the throughput is the lowest. The requirements for spectrum sharing are listed below.

Interference Probability

The first requirement is to probabilistically guarantee the desired SINR in all cells. It is the same as the protection criterion in chapter 3, and please refer to that for details.

$$\Pr\left[\mathrm{SINR_{ins}} \geq \mathrm{SINR_{d}}\right] \geq 1 - p_{\mathrm{out}}, \tag{4.1}$$

where $\mathrm{SINR_{ins}}$ is instantaneous SINR, $\mathrm{SINR_{d}}$ is desired SINR, p_{out} is permissible outage probability.

Throghput

As mentioned above, the second requirement is to determine the lower limit of the cell edge throughput and guarantee that value.

$$C_{\mathrm{min}} = W \log_2\left(1 + \frac{S}{N}\right), \tag{4.2}$$

where W [Hz] is spectrum bandwidth, S is the antilogarithm of the received signal power at the cell edge, N is the antilogarithm of the average noise power.

4.2 Algorithm Combining Power Control and Adaptive Band Control

In an ideal shared environment where the relative distance between cells is long and the cell arrangement has little interference between cells, all cells meet the protection criteria, the throughput exceeds the lower limit, and no power control is required. On the other hand, in a shared environment where the cells are dense, interference between the cells is large and the protection standards cannot be met. Even if the transmission power is reduced by the power control and the interference power applied to each other is reduced, the throughput in each cell is significantly reduced, and the communication quality cannot be guaranteed. Therefore, in this thesis, we introduce the split allocation of the spectrum band that can be used by private 5G operators. Figure 4.1 shows an overview of the spectrum band divide allocation. The purpose is to avoid interference by allocating each spectrum band divided into cells with large amounts of interference.

This thesis proposes an algorithm that incorporates the concept of spectrum band divide allocation into the power control algorithm and selects power control or band divide so that the total throughput is maximized. The details of the power control algorithm are the same as the details in chapter 3. In the band divide method, a spectrum band is divided and each band is assigned to each cell. Here, regarding the method of allocating each cell and each

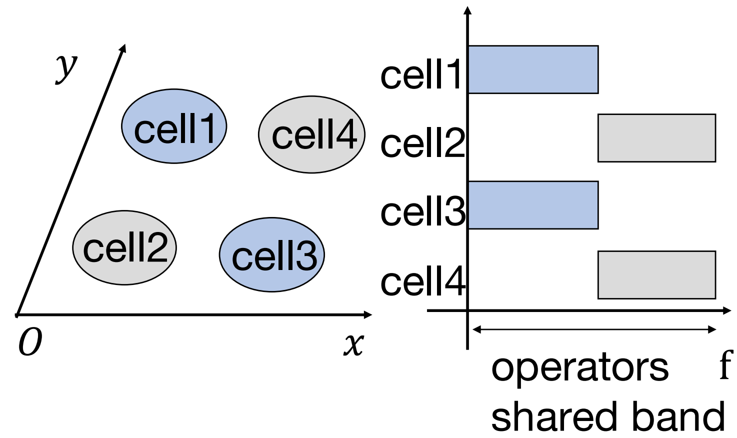

Figure 4.1: Overview of the spectrum band divide allocation.

band, allocation is performed in all combinations of all cells and bands, and band allocation is performed in a combination that minimizes the total interference amount of all cells. If the total interference power that a cell gives to surrounding cells is less than or equal to the noise at the time of the allocation, that cell is assumed to have no effect on other cells, and the entire bandwidth available to the private 5G operator is allocated .

As the initial condition of the cell before executing the algorithm, the transmission power of all cells is set as the maximum transmission power, and only the power reduction control is performed. All cells use the entire band. That is, the cell in the initial state has the largest theoretical throughput. However, there is a great possibility that the protection criteria of all the cells, which is the spectrum sharing requirement, cannot be satisfied. In such a case, the algorithm is executed. The steps of the algorithm are shown below.

Step1

In all cells under the initial conditions, whether or not spectrum sharing is possible is determined based on the spectrum sharing requirement. Here, if the sharing condition can be achieved, the algorithm ends.

Step2

If the sharing requirements cannot be satisfied, the total throughput is calculated for both methods. By comparing the total throughput when dividing the bandwidth into two and assigning it to each cell and the total throughput when executing the power control algorithm, the spectrum sharing requirement and the magnitude of the total throughput are determined. If both methods satisfy the sharing requirements, select the method with the highest total throughput and terminate the algorithm. If one of the methods satisfies the sharing requirements, select that method and terminate the algorithm.

Step3

If spectrum sharing is not possible with both methods, bandwidth division is performed in the initial cell state, and the divided bands are assigned to each cell.

Step4

In **Step3**, select again whether to divide the bandwidth and divide it into three or to execute power control from the viewpoint of total throughput. Here, a trial calculation of the total throughput is performed using both methods. As in **Step2**, check whether each method satisfies the sharing requirements. If both methods do not, proceed to **Step5**. If both methods are satisfied, select the method with the largest total throughput and terminate the algorithm. If one of the methods is satisfied, select that method and end the algorithm.

Step5

Continue choosing and running two algorithms until spectrum sharing is achieved.

4.3 Performance Evaluation

We confirm the usefulness of the spectrum sharing method using an algorithm combining band division and power control through computer simulation. In this simulation, the throughput of the proposed method and the method using only the power control algorithm were evaluated. We also confirmed that the outage probability did not exceed the permissible value with the proposed method. The simulation parameters are shown in Tab. 4.1. In this simulation, cells are arranged from the uniform distribution in the area as in chapter 3. In addition, the average throughput and the maximum outage probability were calculated by changing the cell arrangement 20 times, and the average of the throughput for the 20 times and the maximum outage probability for the 20 times are output to the graph. The initial transmission power is the same for all cells, and the SNR at the cell edge of a cell with a radius of 150 [m] is determined to be 20 [dB]. Outage probability and fading are the same as in chapter 3. In this simulation, the bandwidth assumed to be used by private 5G operators is 4.6 to 4.7 GHz. This is the bandwidth allocated to local 5G, a private 5G in Japan.

Table 4.1: Simulation parameters.

Simulation area [m^2]	1,000*1,000
Mesh size [m^2]	10*10
Number of small cells	2,3,4
Small cell radius [m]	150
Desired SNR [dB]	20.0
Average noise power N [dBm]	-95.0
Reference distance [m]	10
Path loss index	3.5
Operators shared band [GHz]	4.6$\sim$4.7
Lower limit of throughput of the cell edge [Mbps]	10
Permissible outage probability	0.2
Desired SINR [dB]	5.0
Number of trials for SINR	1,000

4.3.1 Characteristic of Average Throughput

First, we evaluated the average throughput when the total number of cells was changed. As a comparison method, the throughput of only power control is derived. Figure 4.2 shows the average throughput characteristics. For each cell number simulated this time, the average throughput of the proposed method is higher than the average throughput of the comparison method at all cell numbers. This suggests that the proposed method is effective for cell placement with a significant reduction in power if only the original power control algorithm is used. In addition, it can be seen that the average throughput decreases as the number of cells increases throughout. The reason for this is that as the number of cells increases, the interference probability per cell increases, and the attenuation due to power control increases.

4.3.2 Characteristic of Outage Probability

Next, the outage probability in the proposed method is evaluated. Figure 4.3 shows the outage probability when the permissible outage probability is 0.2. As in chapter 3, the vertical axis indicates the maximum outage probability among the shareable cells. From Fig. 4.3, it can be seen that all cells simulated this time satisfy the permissible outage probability. On the other hand, when the total number of cells is small, the outage probability is far from the permissible outage probability. Since the relative distance between cells is long and the interference power is small, it is conceivable that the cell arrangement with a small outage probability increases.

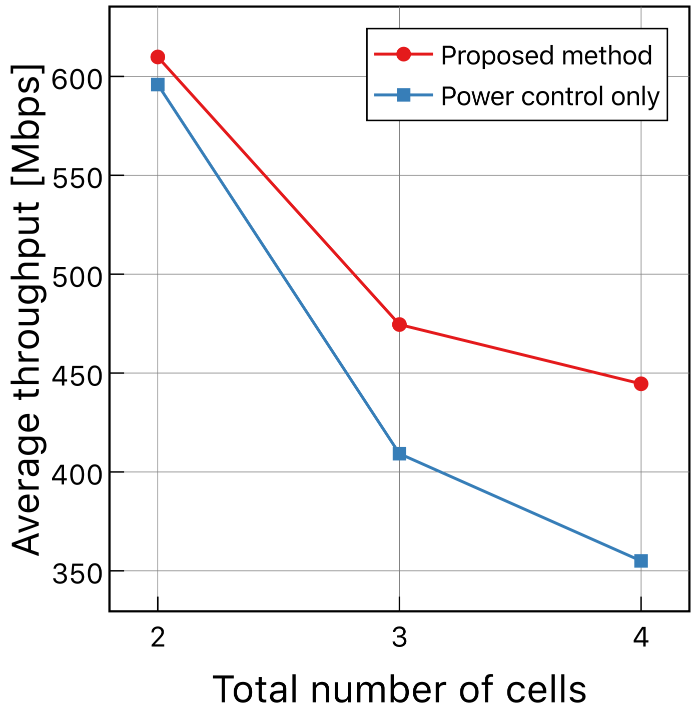

Figure 4.2: Characteristic of average throughput.

4.4 Chapter Summary

In this chapter, focusing on the problem of spectrum sharing method based on power control algorithm, spectrum band divide allocation was introduced into the algorithm. In the proposed method, it is possible to select the power control and the bandwidth divide allocation so that the throughput is maximized. In addition, since the algorithm is executed so as to satisfy the permissible outage probability, it is possible to improve the throughput while satisfying the protection criteria. From the results of the computer simulation, the usefulness of the algorithm was shown by using the proposed method.

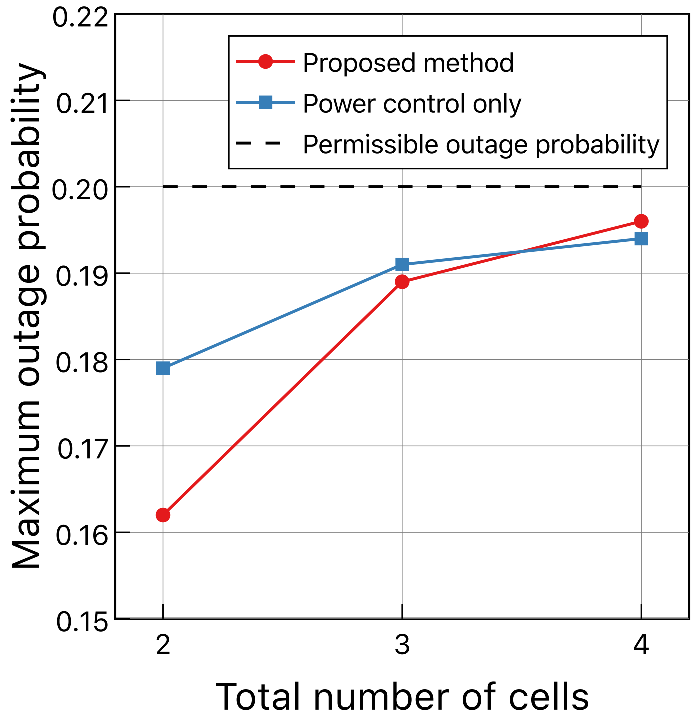

Figure 4.3: Characteristic of outage probability.

Chapter 5

Conclusion

In this thesis, we proposed two spectrum sharing methods in private 5G environment. In chapter 3, we proposed a power control algorithm that performs power control considering the fluctuation of radio propagation due to fading and arranges cells at high density. In the proposed method, the probability distribution of SINR was estimated in the worst mesh of each cell. After that, the transmission power was controlled so as to satisfy the permissible outage probability of the protection criterion, and the spectrum shareable cells were maximized. However, when multiple private 5G operators deploy small cells at close range, a problem has emerged that cell throughput may be significantly reduced. Then, we proposed the concept of spectrum divide allocation and proposed a spectrum sharing method that maximizes the throughput of the whole system by combining spectrum divide allocation and power control algorithm in chapter 4. As a result, the throughput was improved while satisfying the protection criteria of each small cell.

Acknowledgment

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